Climate change
Observations and predictions

Recent research on climate change science from the Hadley Centre

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defra
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Met Office
Hadley Centre

Summary

In this report, we discuss the latest research into climate change science at the Met Office's Hadley Centre for Climate Prediction and Research. In doing so, we are attempting to answer three important questions: Is the climate changing? What has caused the climate to change? And how much do we expect the climate to change in future?

- In the first section of this report, observations of temperature are presented showing that the 20th century warming trend is continuing. The average global temperature over land in 2002 was around 1 ℃ warmer than at the end of the 19th century. Measurements from a number of sites across the United Kingdom and Iceland show that the occurrence of deep depressions, which can cause severe impacts, has changed over recent times. However, this storm record may not yet be long enough to determine whether this represents a long-term trend or whether it is just part of a natural multidecadal oscillation of the climate.
- A considerable amount of evidence already suggests that much of the observed 20th century global warming has been driven by human activity. In the second section of this report, new evidence is presented showing that human activity has caused warming on regional scales too. We also put forward evidence of a human influence on the observed record of atmospheric circulation.
- Finally, we use a climate model to estimate how much human activity could change the climate in the future. Temperature and precipitation changes are presented on a regional basis for the 21st century, and global average changes are shown out to 2200. Future climate change is predicted to vary considerably between regions and some aspects of climate may continue to change long after stabilisation of greenhouse gas concentrations.

These new results highlight the continuing need to monitor the climate and to understand the causes of climate change.
The projections of future climate suggest that without substantial mitigation, further large changes will occur.

During 2003, the Met Office, including the Hadley Centre, moved from Bracknell, Berkshire, to a new state-of-the-art building in Exeter, Devon, in the south-west of England.

Our new working environment will allow us to continue to produce world-class guidance on the science of climate change and to provide a focus in the United Kingdom for the scientific issues associated with climate change.

The models we currently use to make projections of future climate already routinely include the dynamics of the atmosphere and the ocean, and the cooling effects of the atmospheric sulphur cycle. The most sophisticated simulations also include atmospheric chemistry and the carbon cycle, and their feedback on climate change. We have recently commissioned a new supercomputer from NEC, which will increase our computing power by a factor of more than ten. This will allow us to use even more sophisticated models of the climate and to begin to produce the uncertainty estimates, in the form of probability predictions, that are needed for environmental risk assessment and management.

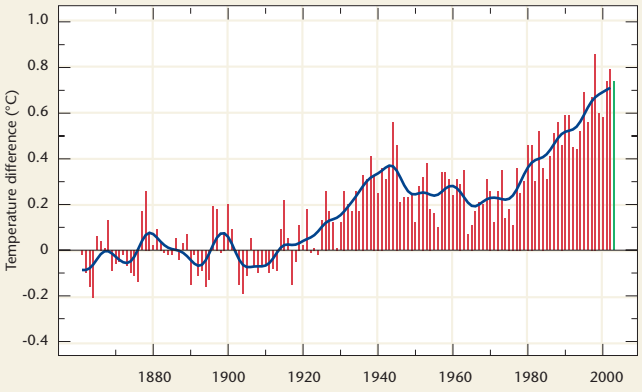
The scientific aims of the Hadley Centre continue to be:

- to understand physical, chemical and biological processes within the climate system and develop state-of-the-art climate models that represent them;
- to use climate models to simulate global and regional climate variability and change over the last 100 years and to predict changes over the next 100 years or more;
- to monitor global and national climate variability and change;
- to attribute recent changes in climate to specific factors;
- to understand, with the aim of predicting, the natural interannual to decadal variability of climate.

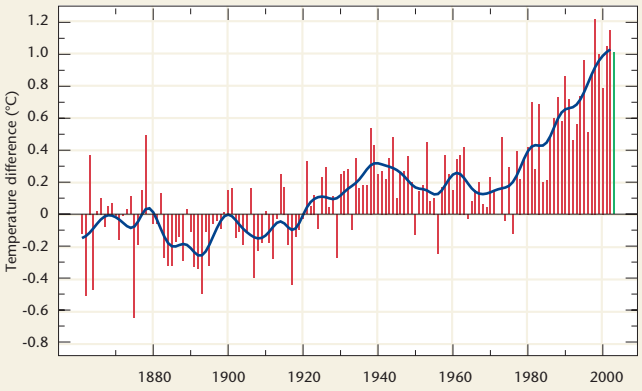
Observed climate change in 2002 and 2003

The climate of 2002

The global average surface temperature in the year 2002 was approximately 0.8 ℃ above the average temperature at the end of the 19th century, making it the second warmest year in the 142-year global instrumental temperature record. The average land temperature was almost 1.2 ℃ above that at the end of the 19th century. In addition to the underlying warming trend due to greenhouse gas increases, 2002 reflected additional warming from a moderate El Nino event in the Pacific.



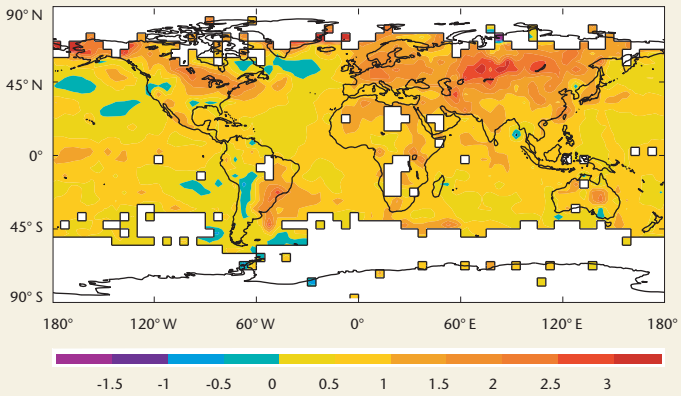
Global near-surface temperatures averaged over the land and ocean. Differences are expressed relative to the end of the 19th century.



Global near-surface temperatures averaged over the land only. Differences are expressed relative to the end of the 19th century.

These results were derived from air temperature records from more than 1,000 land-based weather stations and sea-surface temperature measurements taken from 8,000 ships and buoys. Values up to the year 2000 are combined into a global mean using the statistical technique of 'optimal averaging'.

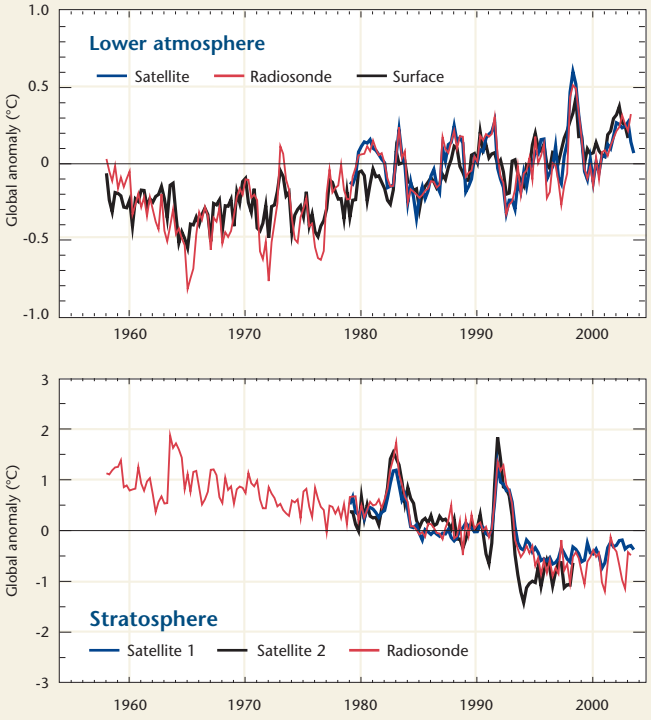
The spatial pattern of temperature change for the year 2002, expressed relative to the end of the 19th century, shows warmer than usual conditions across most of the globe, with Eurasia and a sizeable part of the Indian Ocean being particularly warm. However, parts of the north-east Pacific, Canada, southern South America and parts of Australia were cooler than the reference period.



Difference in temperature (°C) between 2002 and the end of the 19th century. Positive values indicate where 2002 was warmer than the reference period.

The temperature in the atmosphere above the ground is also expected to change due to man's activities. Based on our current understanding of the greenhouse effect, the lowest 10 km or so of the atmosphere (the troposphere) is expected to warm while, above this, increases in carbon dioxide concentration and the depletion of ozone cause the stratosphere to cool.

Radiosonde measurements of the troposphere for year 2002, from around 400 stations and satellite-borne microwave sounding unit measurements, both showed temperatures at heights between 1 and 8 km to be around 0.25 ℃ above the 1981 to 2000 average. This reference period was chosen to reflect the period covered by the satellite measurements.



Global average atmospheric temperatures in the lower atmosphere (troposphere) and in the stratosphere. The results are expressed relative to a 1981 to 2000 reference period.

In the stratosphere, 2002 continued the run of very cold years since the mid 1990s. Large positive temperature spikes during the early 1980s and early 1990s correspond to the short-term stratospheric warming caused by the large volcanic eruptions of El Chichon and Pinatubo.

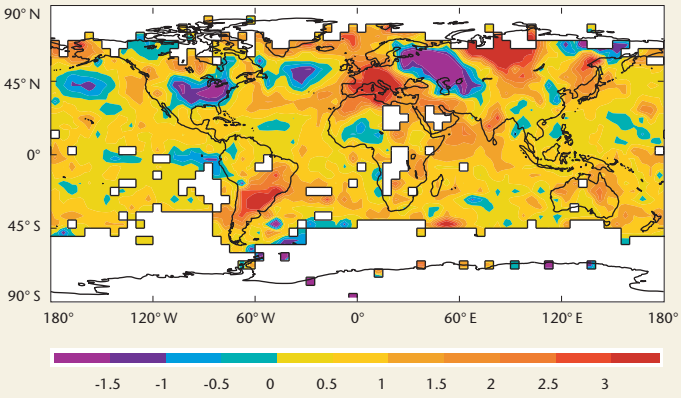
On a global basis, rainfall during 2002 was near the 1960–1990 average, but there were significant seasonal and regional differences. Southern Russia and central Europe suffered excessive rainfall in July and August, leading the Danube and Elbe rivers to burst their banks. In September, southern France also suffered exceptionally heavy rainfall. Conversely, in North Africa the southern parts of the Sahara were the driest since 1990 and the drought in central and southern Ethiopia continued. The summer monsoon rainfall in India was 20% below normal, but rainfall recovered somewhat during August. In the western US a three year drought continued and increased in severity.

The climate of 2003 (January to August)

Globally, the temperature for the first eight months of 2003 was 0.7 ℃ above the annual average temperature at the end of the 19th century. The land temperature for the first eight months of 2003 was 1 ℃ above the annual average over land at the end of the 19th century.

Extreme warmth was experienced over the Northern Hemisphere during the summer months, with June 2003 the warmest on record for a number of areas (the anomalies are shown in the figure below). The Mediterranean region had its warmest combined land- and sea-surface temperature anomaly for June and July on record.

In England, the warmest January to September period was recorded since the Central England Temperature (CET) record began in 1659. On the hottest day of the year, temperatures reached 38.5 ℃ (101.3 ℉), exceeding previous United Kingdom records by the substantial margin of 1.4 ℃.



Difference in temperature (°C) between June 2003 and an average June at the end of the 19th century.

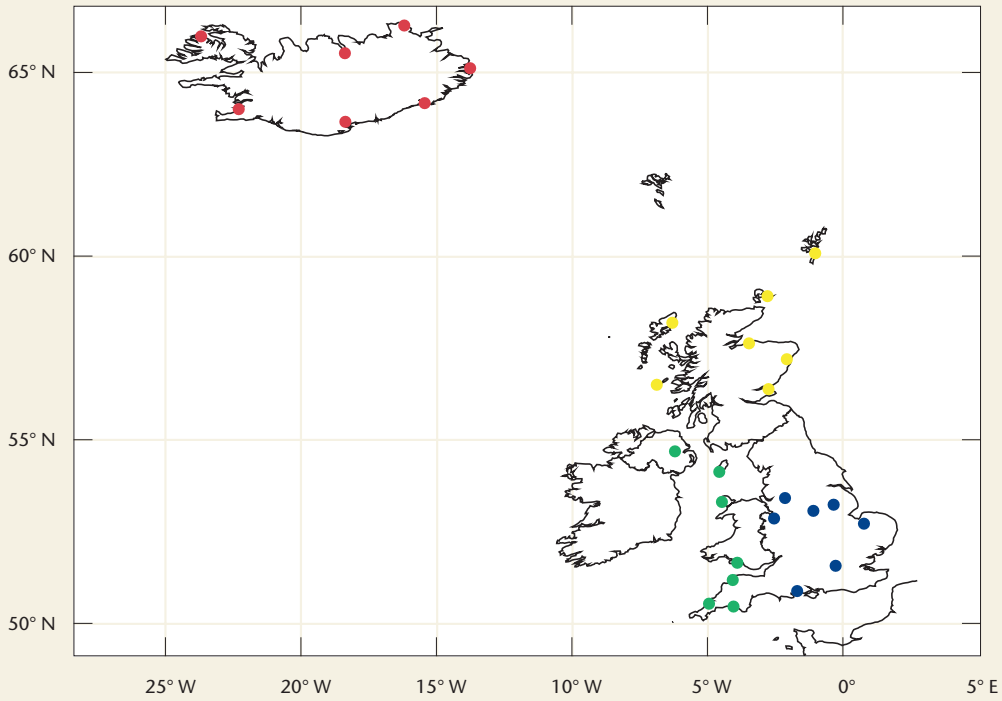
Trends in the number of severe cyclonic storms over Western Europe

The most severe mid-latitude cyclonic storms have serious impacts on people and property. However, these fairly rare and small-scale weather events are difficult to detect in historical observations, especially with daily observations that can miss the fastest moving severe storms.

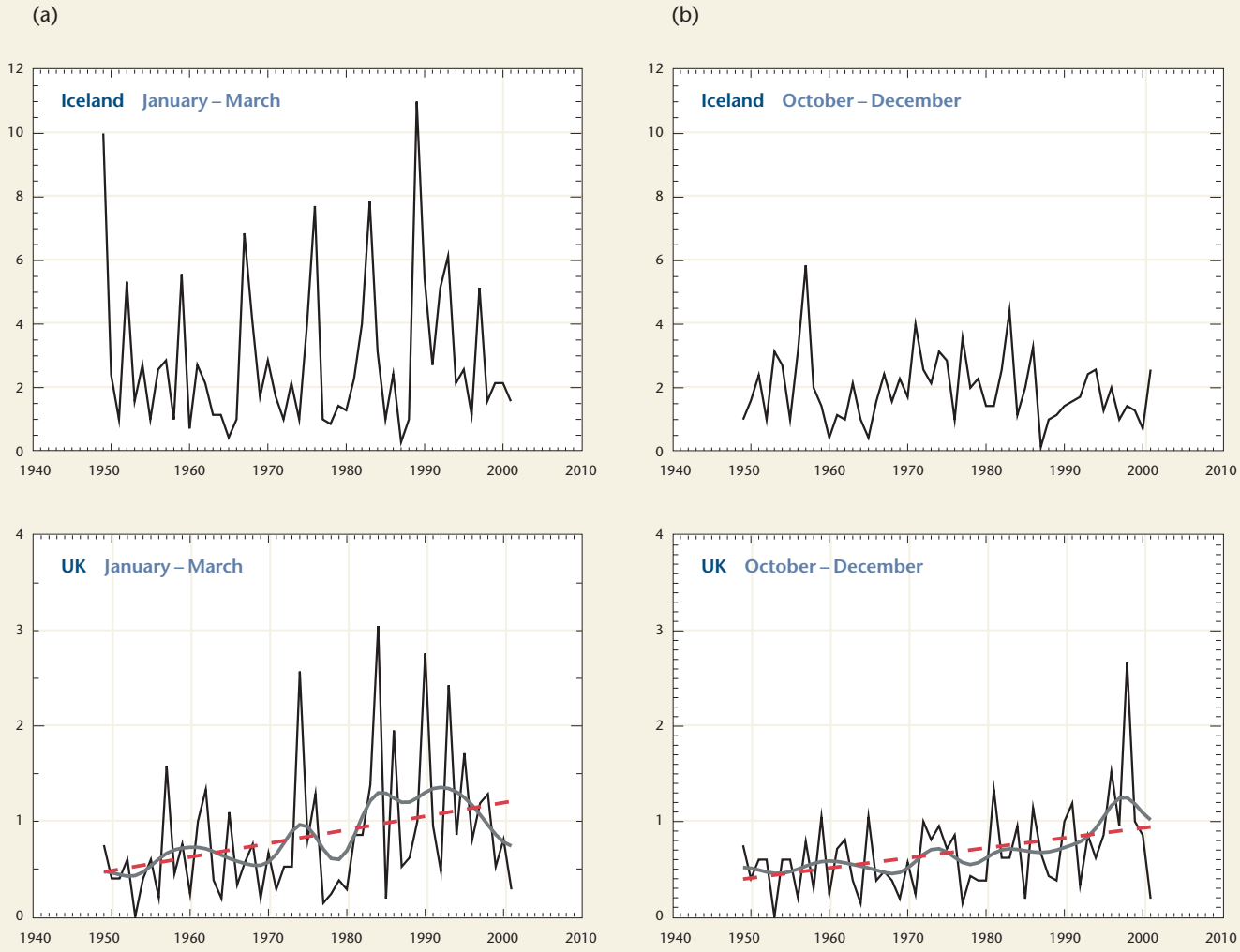
Hadley Centre scientists have recently studied changes in storm characteristics over the past 50 years or so using three-hourly measurements of surface pressure from the United Kingdom and Iceland. Pressure changes were used instead of winds because the results are less sensitive to site moves and instrumentation changes. Observations were available from twenty-one observation sites in the UK and seven in Iceland (figure below).

The average number of storms (per station) shows a significant increase in the United Kingdom winter period (October to March) (figure opposite). Regional analysis shows that the largest increases occur over the southern UK. Iceland has experienced a slight reduction in the number of storms (between October and November), although this reduction can not be separated from natural variability with any degree of certainty. A reduction in storm frequency in the north and an increase in the south is consistent with a southerly movement of the North Atlantic storm track.

A more widely used measure of the storm frequency affecting Western Europe is the North Atlantic Oscillation (NAO) index, which we have compared with the new storm rate analysis. Changes in the NAO index correspond to large-scale changes in the north-south pressure difference across the north-eastern Atlantic. Although there is a similar upward trend in the NAO, there is quite a poor correlation between this figure and the storm rate calculated from the 28 pressure measurement sites. This implies that the severe storms over the UK are more related to strong local gradients of pressure than to the large-scale pressure differences over the Atlantic. However, it is likely that the local severe storms are modified by the long-term changes on the large-scale, which are seen in the NAO index.



Map of observation stations used in the recent study. *The results have been subdivided into regions, shown by different colours.*



The number of storms per observation station over Iceland and the United Kingdom during (a) January to March and (b) October to December. A red trend line indicates that the trend cannot be explained by natural variability (as estimated from these records) alone.

It is also important to place these new results in context. Evidence of storm frequency from daily indices and measurements of wave heights suggest that although it has increased in recent times, the magnitude of storminess at the end of the 20th century was similar to that at the start. This could mean that natural variations in the magnitude of storminess on timescales of several decades or more are responsible for all or part of the trends seen in these new results and that data covering a longer period is needed in order to distinguish a climate change trend from the natural variability.

Human influence on regional climate

Observations of temperature show that on average the globe has warmed substantially over the 20th century but that there have been large regional variations in the amount of warming (page 2). The Intergovernmental Panel on Climate Change (IPCC) concluded in their Third Assessment that there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities [(1)].

Previous analyses have looked at temperature changes over the globe as a whole rather than over individual continents, but recently the Hadley Centre has examined the causes of 20th century temperature change on the continental scale. Here, the focus is on the landmasses of North America, Asia, South America, Africa, Australia and Europe. The modelling study investigated the historic impact on the climate system of:

- greenhouse gases alone;
- the combined effect of anthropogenic sulphate aerosol, lower atmosphere and stratospheric ozone;
- the combined effect of volcanoes and changes in the output of the sun.

The optimal detection method (see box below) shows there is a significant greenhouse gas warming signal in all of the continental regions considered (opposite, left). Temperature changes from other anthropogenic and from natural factors are detected in some but not all of the continental areas, since these forcings are weaker and more uncertain than greenhouse gas forcing. Therefore, we have more confidence in attributing a man-made greenhouse gas component to continental scale temperature changes than in attributing other factors.

The far right figure shows the temperature changes in the model results compared to the observations for each continental region. The increases in greenhouse gases caused increased warming as the century progressed. This was balanced to a greater or lesser degree, depending on region, by aerosol cooling. In general there is good agreement between observed and simulated changes.

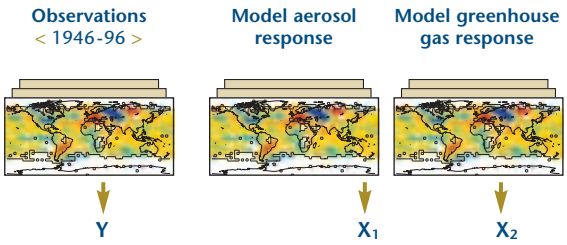
Footnote:
(1) Page 158 of Climate Change 2001. Synthesis Report. IPCC.

Attribution methodology

Attributing observed climate changes to specific causes uses a mathematical technique called 'optimal detection'. Here, the simulated climate response to each potential cause of climate change in isolation is weighted. This is done in such a way that when all the weighted responses are added together, the result gives the closest approximation to the observed pattern of warming. The weights for each pattern (or cause) of climate change also have an uncertainty range attached. If the whole of this range is above zero for a specific cause, then we can claim to have detected climate change due to that cause.

An added bonus of the attribution methodology is that it provides a measure of how well our climate model simulates the magnitude of the response to different forcings. This helps to validate the climate model and can highlight which parts of the model might benefit most from improvement.

Optimal detection

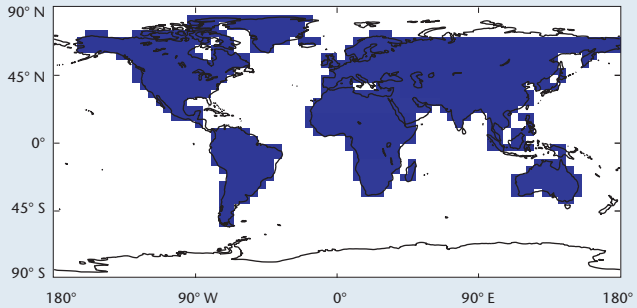


$$Y = NOISE + ß_1 \times X_1 + ß_2 \times X_2$$

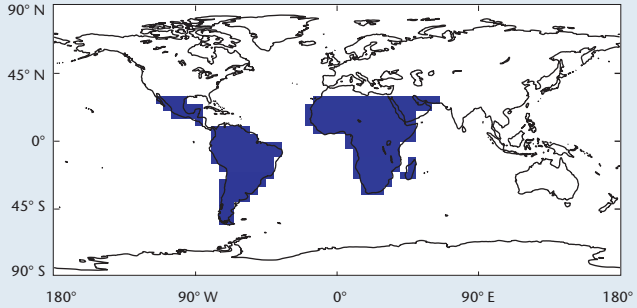
Y is the time varying pattern of observed climate change, X_1 is the time varying simulated response to aerosol particles and X_2 is the time varying response to greenhouse gases. $ß_1$ and $ß_2$ are the weights of the responses to aerosols and greenhouse gases separately.

Additional climate response, such as the response to solar intensity changes or volcanic eruptions, can also be included.

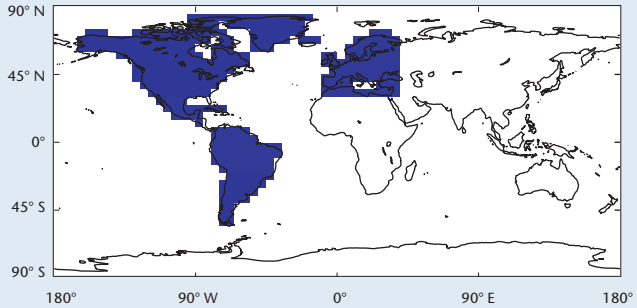
Greenhouse gas signal



Sulphate aerosol signal

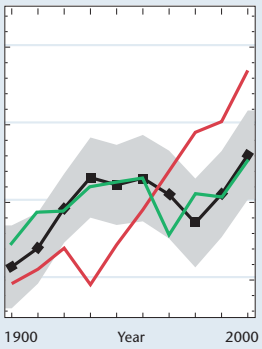


Volcanic and solar signal

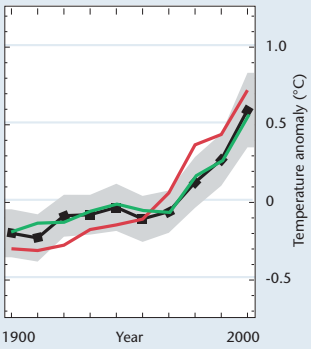


Regions where a signal has been detected are coloured blue. Results for the greenhouse gas, sulphate aerosol and natural forcings are shown separately.

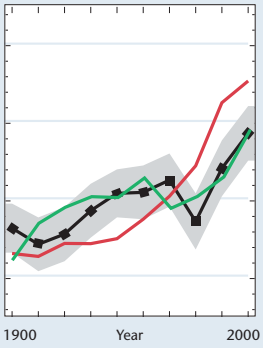
North America



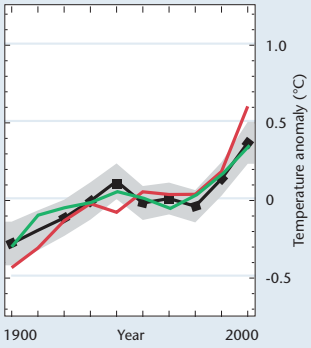
Asia



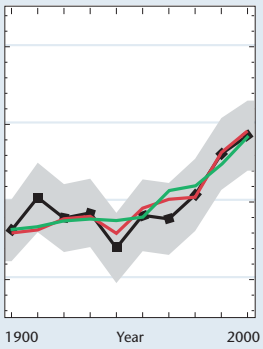
South America



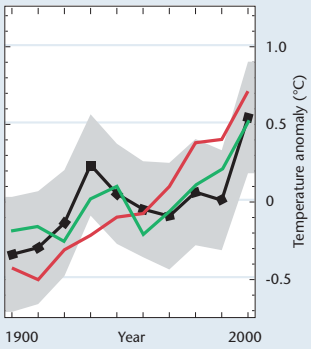
Africa



Australia



Europe



Comparison of the simulated and observed 20th century temperature changes.

Observations

Simulation with greenhouse gases

Simulation with the combined effect of greenhouse gases, aerosols, solar and volcanic forcings

Other evidence for human influence on the climate system

Most attempts to determine the cause of climate change have used temperature observations. The results provide strong evidence that increases in greenhouse gases, which result from fossil fuel burning and changes in land use, have been the major cause of surface and lower atmospheric warming during the 20th century.

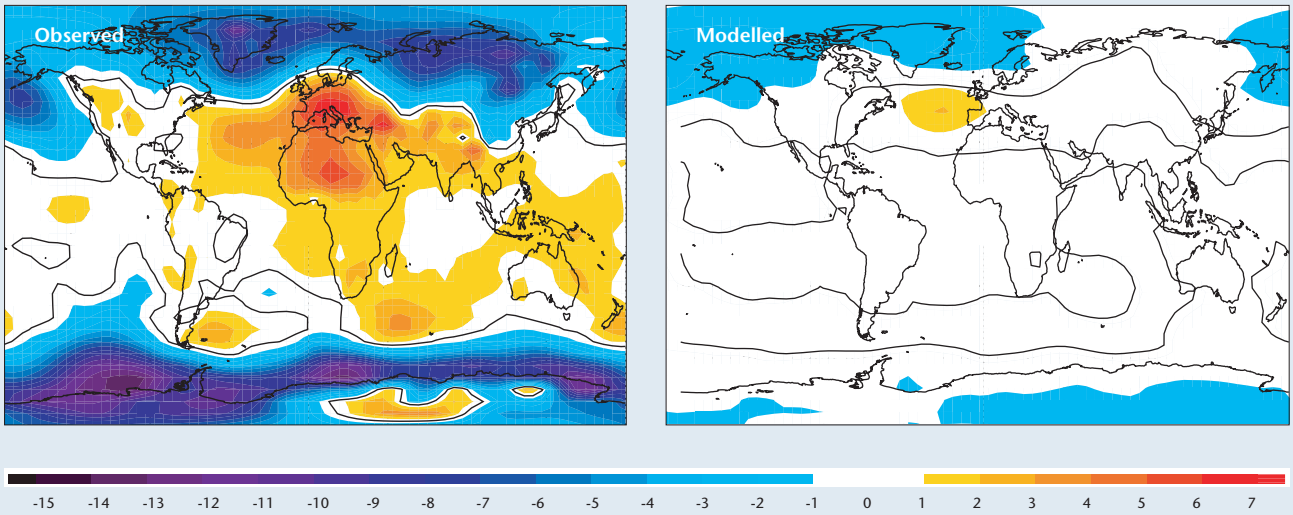
But greenhouse gas-driven climate change affects more than just temperature. New work, involving a collaboration between the Hadley Centre, the Meteorological Service of Canada and the University of Victoria, has looked at whether observed changes in atmospheric surface pressure, and hence winds, have also been influenced by increases in atmospheric greenhouse gases.

The observed trends in winter atmospheric surface pressure (below) for the last 50 years show increases over the subtropical North Atlantic Ocean, southern Europe and North Africa. Decreases in surface atmospheric pressure occurred over the polar regions and the North Pacific Ocean. The patterns of pressure change simulated by coupled-climate models for the same period have many of the same features as the observations, but the magnitude of pressure change is much smaller. This could mean that climate models underestimate changes in surface atmospheric pressure, in which case this could be an area where the models might be improved in future.

When the mathematical attribution method of 'optimal detection' (see box on page 6) is applied to the pressure data, it is found that anthropogenic emissions of greenhouse gases and sulphate aerosols have had a clear influence on surface pressure in the second half of the 20th century. In fact, there is less than a 5% chance that the observed changes in surface pressure can be explained by natural climate variability.

This new result provides further evidence that human activity is changing climate.

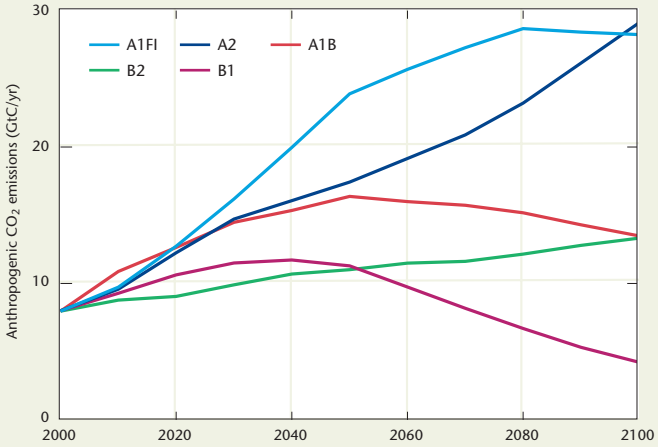
(a) (b)



Observed (a) and modelled (b) patterns of pressure change (hPa). The model result is the average of four different climate models.

Predictions of future climate change

New predictions of future climate change have been produced by the Hadley Centre for five scenarios of future emmisions from the IPCC (below). The projections were made using a coupled ocean-atmosphere climate model. The main underlying characteristics of the scenarios are summarised in the figure and table below.



Anthropogenic carbon dioxide emissions for IPCC SRES scenarios.

Name	Economic change between 1990 and 2100 from GNP increase (Trillion US$)	Population by 2100 (million)	Cumulative CO_2 emissions between 1990 and 2100 (Gt/C)
A1FI	505	7140	2190
A2	225	15070	1860
A1B	510	7060	1500
B2	215	10410	1160
B1	310	7050	980

Assumptions made in the IPCC Special Report on Emmisions Scenarios (SRES) to derive future emmisions of greenhouse gases.

The global mean temperature rise over the 21st century is predicted by the Hadley Centre model to be 4.5 °C for the highest emmisions (A1FI) and 2 °C for the lower (B1) (overleaf). We use the A1B scenario (which is near the middle of the emission range) to illustrate a number of potential features of the future climate. It projects a global mean temperature rise of 3 °C.

How do we know that climate models produce credible results?

Three-dimensional models of the climate are verified against observed changes before being used to make future climate projections. Some of the main techniques for validating the models are as follows.

Comparison against recent past change

Observations of climate quantities from numerous sites around the globe are available from recent decades. Some isolated records, such as the Central England Temperature (CET) record, go back a few hundred years.

A climate prediction index has been developed by the Hadley Centre as a means of comparing the performance of our models against a range of different indicators (such as surface temperature, rainfall and surface pressure) using a single number.

Comparison against observed climate variability

The climate varies naturally from day to day, month to month, year to year, and on longer timescales. Occasionally this variability leads to extremes of temperature or precipitation. An important test of a climate model is whether it can credibly reproduce the observed natural variability.

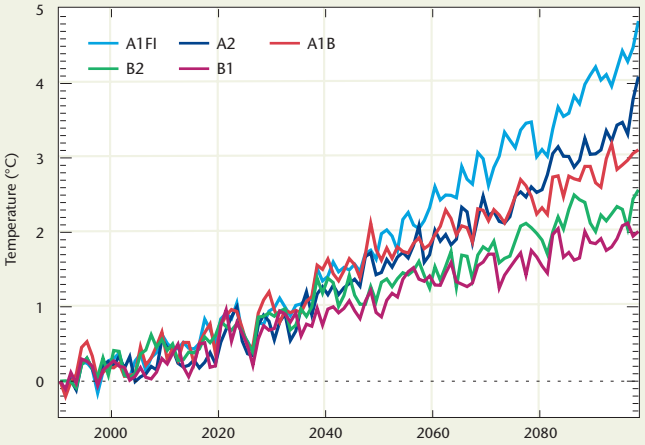
Comparison against paleo-climate measurements

Climate models can be used to simulate climates of the more distant past, such as the Last Glacial Maximum (the peak of the last ice age, c.21000 BC). Model results are compared to 'proxy measurements' of past climate changes, such as width and density measurements from tree rings or layer thickness from laminated sediment cores.

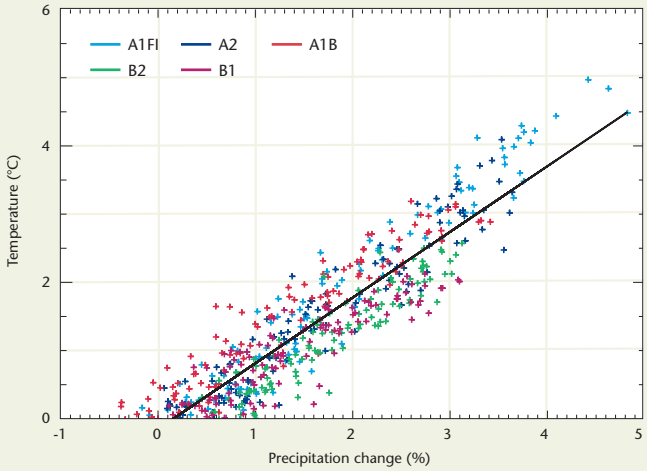
The advantage of testing a model against both recent measurements and past climates, such as the Last Glacial Maximum, is that the model has then been validated for a large range of different climate conditions.

Continued

Predictions of future climate change



Predicted global average temperature due to five IPCC SRES emission scenarios.



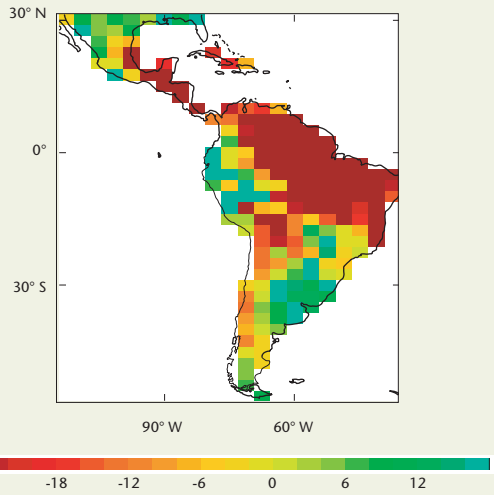
Hydrological sensitivity of the Hadley Centre model.

Over the next 40 years the warming predicted for the five scenarios is similar, despite there being significant differences in the amount of greenhouse gas emissions for each case. This is because the long lifetime of atmospheric carbon dioxide and the large thermal inertia of the climate system mean that much of the change over the next few decades is already built into the climate system from present day emissions and those from the last few decades. By the same token, the climate outcome for the latter half of the 21st century will strongly depend on the emissions over the next few decades.

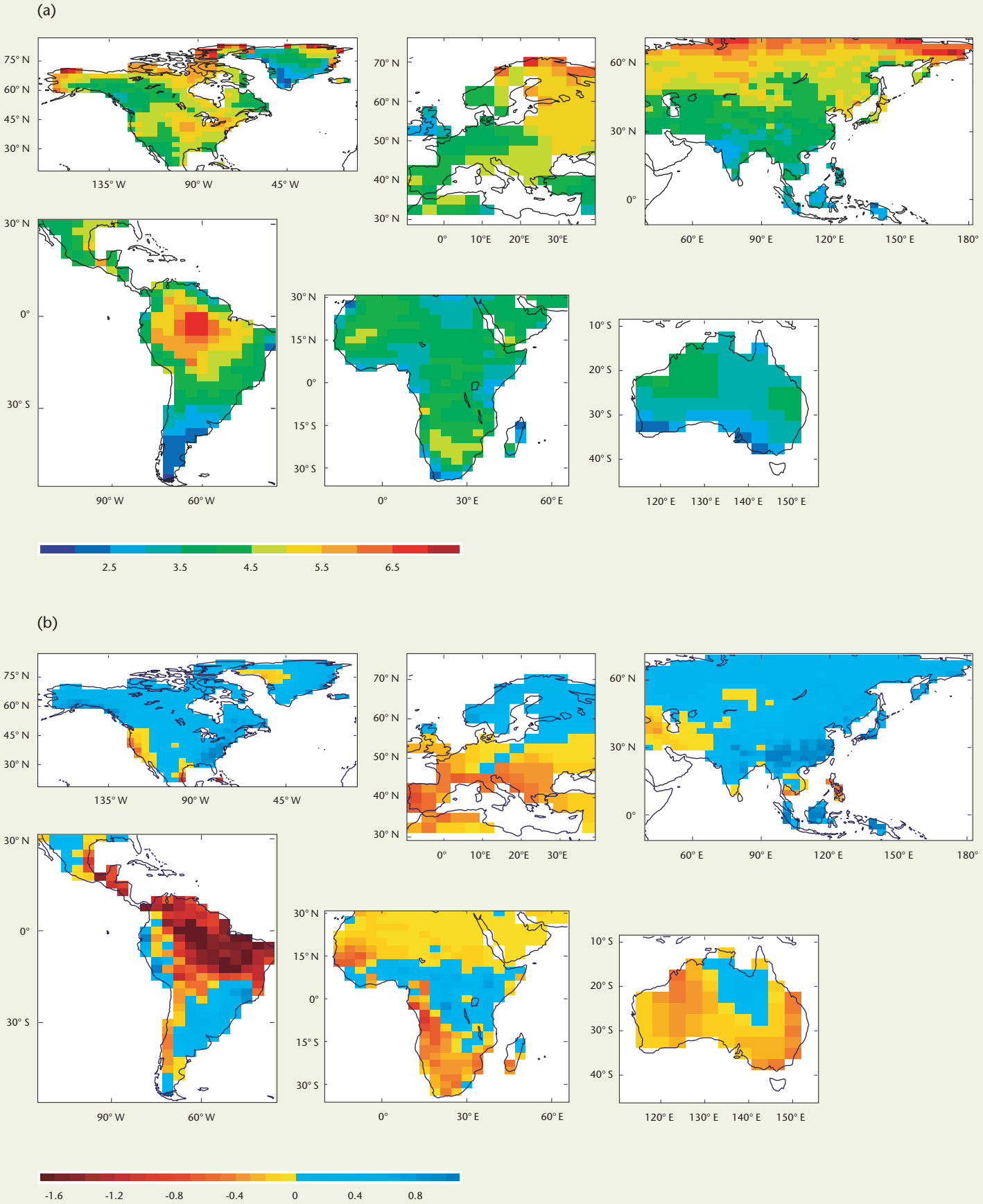
As global temperatures increase the earth's water cycle becomes more intense and rainfall increases. The figure (above right) shows that global precipitation increases by around 1% for every 1 °C of warming in the Hadley Centre climate model for all the SRES scenarios. In the case of A1B the precipitation increase during the 21st century is predicted to be almost 3.5%.

It is well known that the temperature and precipitation changes during the 21st century will vary from location to location. Here, regional change in the six continental areas of North America, Asia, South America, Africa, Australia and Europe are presented for the A1B scenario (opposite).

Over the North American continent, Europe, Asia, and Central and South America the temperature rise is predicted to be around 4.5 °C. Over Africa and Australia the temperature rise is less, at around 3.5 °C. Increases in precipitation are predicted over North America, northern Europe, much of Asia, and central Africa. Decreases in precipitation are predicted to occur over southern Europe, most of Australia, northern and southern Africa and parts of South America. Over some areas the combined effect of a rise in temperature and a reduction in precipitation is a significant fall in the amount soil moisture, as shown below for South America, which may impact on agriculture and food production.



Predicted change in soil moisture (mm) over South America between present day and the 2080s for the SRES A1B scenario.

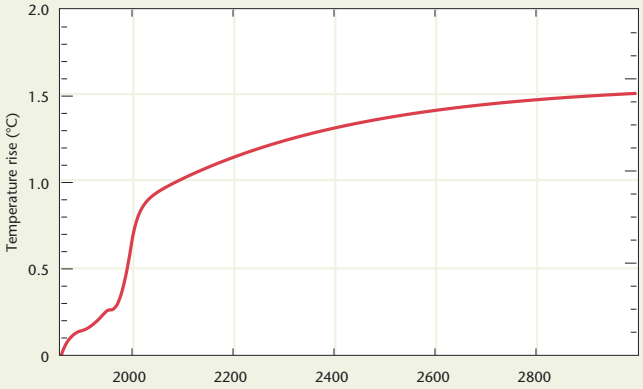


Predicted change in (a) temperature (°C) and (b) rainfall (mm/day) between present day and the 2080s for the SRES A1B scenario.

The effect of stabilising greenhouse gas concentrations at year 2100

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve "… stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system."

Even after greenhouse gas concentrations are stabilised, it will take a considerable amount of time for a balance to be reached between the incoming solar radiation and the heat lost from the planet. If greenhouse gas concentrations were stabilised today, which would require an immediate reduction in emissions of around 60%, we would still expect the temperature to eventually rise by another 1 °C due to the inertia of the climate system (below).



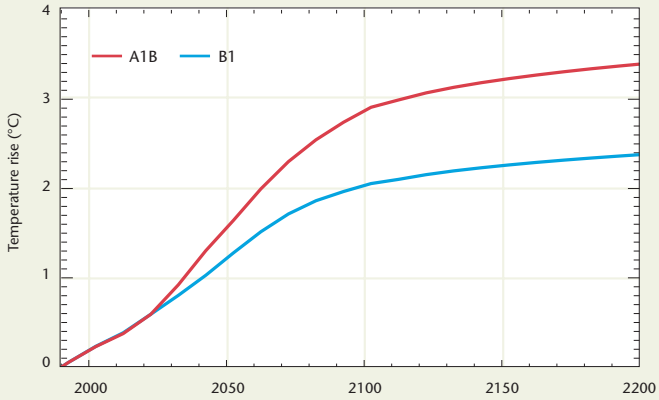
The rise in global average temperature following stabilisation of greenhouse gas concentrations at present-day levels.

In this section of the report, we present our first estimates of the temperature and sea-level rise during the 22nd century for two scenarios:

- IPCC SRES **B1** emissions and concentrations up to 2100 followed by constant greenhouse gas and aerosol concentrations at year 2100 levels for 100 years;
- IPCC SRES **A1B** emissions and concentrations up to 2100 followed by constant greenhouse gas and aerosol concentrations at year 2100 levels for 100 years.

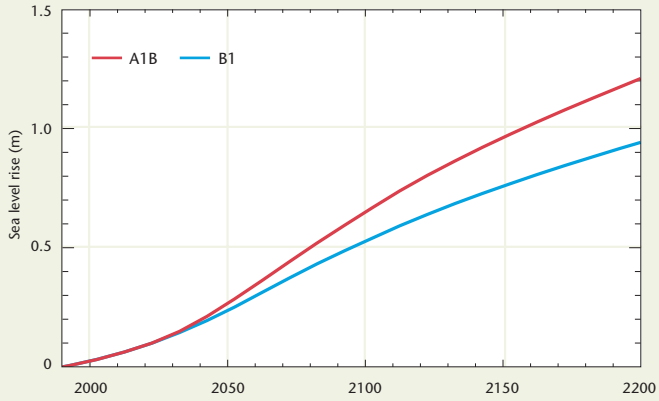
Note these scenarios imply unrealistically sharp reductions in emissions at 2100, but are used here to give a general impression of two approximate stabilisation concentration profiles.

The following results were calculated using a simple climate model and will be repeated using our full coupled ocean-atmosphere model. The figure below shows that for both stabilisation scenarios the global mean temperatures continue to increase between 2100 and 2200, but at a reduced rate.



The predicted rise in global average temperature for scenarios that stabilise greenhouse gas concentrations at 2100.

The sea level also continues to rise beyond the 2100 concentration stabilisation point. On this timescale the major component of the sea-level rise is the thermal expansion of the oceans. Because the oceans have a large thermal capacity they take a long time to adjust to changes in atmospheric greenhouse gas concentrations, and the commitment to future sea-level rise beyond 2100 (expressed as a percentage of the 21st century rise) is much greater than the commitment to temperature rise. The rate of sea-level rise 100 years after stabilisation is only slightly less than the rate when stabilisation occurred.



The predicted global average sea-level rise for scenarios that stabilise greenhouse gas concentrations at 2100.

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